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An Informational Approach to Skill Transfer

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This research program studied the nature of fundamental skills underlying the expertise of aircraft pilots. The research program included a review of the issues facing flight instruction. The specific tasks of landing a light aircraft and of navigating an aircraft through an unfamiliar area were selected for intensive study. The experimental projects undertaken in this program used a flight simulation system developed around a real-time computer-generated visual display. Two experimental paradigms were exploited. One was used to explore the visual information and skills used to support the aircraft landing task. As a means of identifying critical sources of information, experiments with experienced pilots examined how distortions in the simulated visual scene affected landing performance. The second paradigm evaluated transfer in a mission rehearsal task. A navigational database was developed and displayed via the visual simulation system. Flight students were taught navigational skills under different experimental conditions and were then tested in a realistic navigation condition.

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An Informational Approach to Skill Transfer

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Contents

List of Figures

ABSTRACT

Relatively little is known about the nature of fundamental skills underlying complex real-world tasks or how those skills are learned. The expertise of aircraft pilots was selected as a domain of suitable complexity and relevance. This research program was initiated with a review of the issues facing flight instruction. That review suggested several areas that were ripe for investigation, one of which related to the type of information used in piloting an aircraft and how pilots developed sensitivity to that information during flight instruction. The specific tasks of landing a light aircraft and of navigating an aircraft through an unfamiliar area were selected for intensive study. The experimental projects undertaken in this program used a flight simulation system developed around a real-time computer-generated visual display. Two experimental paradigms were exploited. One was used to explore the visual information and skills used to support the aircraft landing task. As a means of identifying critical sources of information, experiments with experienced pilots examined how distortions in the simulated visual scene affected landing performance. The second paradigm evaluated transfer in a mission rehearsal task. A navigational database was developed and displayed via the visual simulation system. Flight students were taught navigational skills under different experimental conditions and were then tested in a realistic navigation condition.

Importance of Transfer

Some notion of skill transfer underlies all applied training programs. No matter what training environment is used, the ultimate concern is with how well trainees perform in the operational environment. While the strategy used to evaluate transfer is relatively easy to understand, satisfactory evaluations can be difficult to accomplish. In military settings, the operational activities that are the focus of training programs (actual conflict with a hostile enemy) may never be available, and even when they are it remains difficult to link operational deficiencies to training deficiencies.. For many military requirements, the realistic exercises that could verify the effectiveness of training are so costly that they will rarely be used for that purpose. One alternative is to understand issues of transfer at such depth that it would be possible to analyse a specific training program in terms of established principles of transfer.

The goal of the proposal outlined here is to develop an understanding of human action in terms of the critical elements that support skilled performance and that support the transfer of skill. Within the program outlined here, the fundamental assumption is that informational properties of the task are a key element in skill transfer. During learning, trainees become sensitive to a relatively small set of low-dimensional relational or abstract properties in the task environment, and if those properties support performance in the operational task, high transfer will result. It should be noted that the theory developed here does not exclude the involvement of other properties that might better be characterised in terms of cognitive or action properties. The approach does, however, suppose that non-informational properties will be similar in character in that they will be low-dimensional relational or abstract properties, and that their identification will succumb to a similar strategy as that outlined here for informational properties.

Informational Invariants

The transfer perspective to be explored draws on the ecological theory of perception as developed by Gibson (1979). Human action is supported by information derived from critical relationships in the environment. That information will be specific to the layout or the structural properties of the environment and also to relative motions or kinematic properties generated by an observer's own actions. Such relationships have specific values that remain invariant while an actor is performing correctly but that have different values when he or she is performing poorly. With aircraft landings for example, one or more relationships will be invariant if the pilot remains on the designated approach glideslope. Those relationships will change, however, if the pilot deviates from the designated glideslope, and the ability of the pilot to recognize that deviation and to correct for it depends on his sensitivity to changes in the relationships that specify correct or accurate control.

Gibson (1979) characterizes such relationships as "invariants". Within a changing sea of information the individual character of an event will be perceived because of some specifiable property or relational value. That property or relation will remain constant across events perceived as similar but will differ between events perceived as different. Thus, an invariant is a property of an event that remains unchanged as other properties change; that which specifies the persistent character of the event (Gibson, 1979). It may have both spatial and temporal extent. Following Stoffregen and Riccio (1988), an invariant may be viewed as a lawful relationship between patterns of stimulation and properties of the task.

Information for Manual Control

For invariants to be of use in a theory of human action it must be possible to isolate them analytically and to test their effects on behavior. For example, an invariant to judge the speed of self motion might be derived from the rate of optic flow. Where speed and distance to visible surfaces remain constant, the relative rate at which visible elements in a scene pass by a moving observer will normally be constant. The perceived invariance of flow can, however, be disrupted by inhomogeneity of element distribution. Denton (1980) evaluated the influence of this latter factor in a driving simulator with a visual display. Pattern distortions in which elements became more compressed throughout a trial caused subjects to reduce their simulated speed despite instructions to maintain it constant. This experiment indicates that an invariant relative rate of visual flow can be used to maintain velocity and that distortions of the invariant will have predictable effects.

Goals of the current project

The work undertaken in this program prior to this funding cycle explored transfer in relation to aircraft landings and had identified some invariant properties relevant to the control of an approach to landing. For this funding cycle it was thought desirable to expand the range of tasks that would be explored as well as to seek better methods of identifying invariant properties. Four distinct elements of work were undertaken:

- a comprehensive review of flight training issues in order to identify productive scenarios in which the implications of the theory could be tested.
- Examination of transfer effects within a scenario selected on the basis of insights derived from that review.

- Continuation of the landing research to clarify the informational properties that support the landing approach.
- exploration of more powerful analytic methods than have been used in the past to identify information sources for landing.

Review of flight training issues.

A primary claim from Situated Cognition is that learning is ineffective if removed from the context in which the target skills must be deployed. This claim is inconsistent with many of the mainstream approaches to education and cognition. In Lintern (1994) I describe what it means to be situated and outline the central issues raised within the literature on Situated Cognition. These ideas have several important implications for aviation education and training. Principles drawn from the research in Situated Cognition are discussed in terms of their relevance to current and potential practices in flight instruction.

Several independent features emerged from that analysis of ethnographic work and were posed as possibly central to the power of situated learning. Instead of emphasizing the instructor as the source of knowledge they shift focus to the self-organizing potential of a learner as shaped by the structuring power of the situation. In addition, each of the features emerging from this review has implications for how we might proceed with the design of an instructional program that must, for reasons of cost or safety, be removed from the natural setting. It is these implications that would seem relevant to any discussion of flight instruction within a virtual environment.

Much simulator design work is undertaken with only peripheral guidance from active pilots. The work described by Thomas and Geltmacher (1993) on the development of visual displays for air combat simulators offers an example. It remains unclear whether these technological developments can contribute positively to training effectiveness. Nowhere in their description do Thomas and Geltmacher refer to the manner in which such a system might be used or how its training effectiveness might be evaluated. The implication of their description is that this is a problem for hardware development and visual science but not for instructional science.

Failure to heed the lessons of Situated Learning may lead to the development of training programs that introduce breaches between instruction and practice as noted by Jordan (1989), Lave and Wenger (1991), and Hutchins (1992). Training devices and instructional strategies can introduce one type of breach. For example, motions system may enhance sensitivity to perceptions that are not representative of those induced by aircraft motion or to perceptions that skilled pilots disregard (Lintern, 1989). Part-training strategies and manipulations of task difficulty may create tasks that differ in critical respects from the criterion task (Lintern & Gopher, 1978; Wightman & Lintern, 1985). While these breaches between instruction and practice may be more subtle than those noted by Jordan (1989) they are equally invidious. In addition, current methods of training must be adapted to instructional requirements for modern, high technology cockpits. One implication of the results from Sarter and Woods (1992) is that these adaptations have not been entirely successful.

Transfer within a mission rehearsal scenario.

With such a diverse set of elements appearing important it seemed that a mission rehearsal scenario with a heavy cognitive component might be a suitable experimental task with which to test the relevance of the information theory of transfer to the insights drawn from the review of situated learning. A flight simulator and a computer-generated depiction of an environment with both natural and cultural features were used to teach and test navigation knowledge (Bone & Lintern, 1999). Conditions of guided rehearsal, unguided rehearsal and map study were used to familiarize subjects with the navigation environment. A route-following test of navigation knowledge in the simulated environment was used tot test the development of route knowledge.

The acquisition of survey knowledge was also tested. This form of knowledge remains important even for a prespecified course because unanticipated events may require a diversion to a new course. The prevailing view in the literature is that survey knowledge is better developed by map study than by active rehearsal of a specific route (Thorndyke & Hayes-Roth, 1982; Williams Hutchinson & Wickens, 1996).

Method

Participants

Thirty-six active pilots (31 males, 5 females) participated in the experiment. The median age was 23 years and the median total reported flight time was 272.5 hours. All participants had a private pilot license (or the military equivalent) and prior experience in cross-country navigation (median = 80.0 hours). They were paid $7.50 for a session which lasted slightly over one hour.

Simulator

The navigation mission was undertaken in a simulator, which was comprised of a joystick, simplified helicopter-like dynamics, and a computer-generated visual scene. The control was a FlightStick model joystick manufactured by CH Products A top pushbutton was used to start each trial and the trigger was used to signal start and stop times for the pointing task. The joystick permitted first-order control of pitch and bank angle. Airspeed was set to 115 knots although airspeed varied throughout the flight to a minor extent in climbs and descents. Thrust and yaw were automatically set by the system. Flight instrumentation was displayed on a Silicon Graphics 16-inch (40.64 cm) color monitor located 90 cm in front of the subject's eye-point. The monitor was positioned so that it did not restrict the view of the computer-generated visual scene. A radar altimeter located on the right side of the monitor displayed altitude above ground level (AGL). An attitude indicator located in the center of the display showed the chosen pitch attitude as well as bank angle. The system was limited to a maximum bank angle of 30 degrees. The heading indicator was located at the top of the monitor. The heading indicator was removed from the flight display for the testing session.

The visual scene was generated with an Evans and Sutherland SPX500T image generator with an update rate of 50 Hz. Two Electrohome ECP 3000 color projectors were used to project the images on two screens each measuring 228.6 cm high and 304.8 cm long. One screen was positioned 300 cm in front of the subject and the other was offset to the subject's left at the same distance from the subject, adjoining but set at a 115 degree angle to the other screen. The two screens allowed a 38-degree vertical by 112-degree horizontal viewing angle (27 degrees to the right and 85 degrees to the left of centerline). All but one of the turns within the navigational environment were to the left. The center screen was adequate for straight-ahead flight but the left screen provided additional useful detail for turns to the left.

The Navigation Task

The navigation area was approximately 13.5 by 13.5 nautical miles . The topography of the area included both flat and hilly terrain with rivers, roads and buildings. A course of five legs of 22.3 nautical miles total length (individual legs ranged from 3.7 to 5.0 nm) was to be flown through the environment. The range in altitude of this course was 750 feet. Maintenance of 150 feet AGL required vertical speeds of approximately $\pm$ 1500 fpm in the climbing and descending portions of the route.

An automatic procedure was programmed to reset subjects to the start point for the next leg (with heading aligned with the course of that leg) if elapsed time for the current leg was 30% greater than a criterion time. That criterion time had been established from the time taken by an experimenter to fly it with the guidance available.

The low-detail world used in the rehearsal flights contained all of the same objects as the high-detail world but differed in the appearance of those objects. In the low-detail world the portrayed hills appeared to be more block-like than those of the high detail world. Additionally, all objects such as buildings and bridges were represented as gray blocks. In development of this representation the intent was to use a level of detail that would be available with a less expensive image generation system.

Procedure

Participants were randomly divided into three groups: map study, unguided rehearsal, and guided rehearsal.

Familiarization

Participants were given a practice flight of approximately five minutes through a low-detail navigation area that was not part of the area used in the remainder of the experiment. They were required to follow a route depicted by a red line. They were instructed to use 30 degrees of bank for at least one turn since this was what they would be using in the subsequent trials. The primary purpose of this session was to familiarize participants with the characteristics of the simulator and with the control requirements of the main experimental task.

Mission Rehearsal

After familiarization, participants were given the preparatory experience specific to their group. The map-study group studied the predetermined route on a map of the navigation environment. They studied the map as they chose for 12 minutes and then were required to spend another 12 minutes mentally tracing the path, stating aloud landmarks that they would pass along the route and the heading they would be required to fly for each leg.

Both the guided and unguided rehearsal groups were exposed to the navigation task by having them fly twice along the predetermined route in the low fidelity version of the simulated environment. On the first flight, participants followed the path and observed as they deemed appropriate. During the second flight they were required to identify landmarks as they passed them and to state the approximate heading for each leg. Each of these flights lasted approximately 12 minutes.

For the guided rehearsal group, a red line showed the predetermined route. This group did not have access to the map on either of the rehearsal flights. The unguided rehearsal group flew the same low-detail depiction as the guided rehearsal group but without the red line and with the map for route information. Participants in this group were given approximately 30 seconds to examine the map's detail and its legend prior to the first rehearsal flight. The intent was to be sure that they understood the map layout without actually studying the route or the simulated area.

Testing

There were two testing tasks. The first was to point to each of several targets. Participants were placed at the start of a leg and on the course heading of that leg at 150 feet AGL. They were stationary but could pivot via the joystick. They were to start the trial by squeezing the trigger on the joystick after a prompt and then pivoting in the estimated direction of the target as if they were going to fly towards it. The time required to point to the target and the bearing error to the target were recorded. There were either two or three targets for the start point of each leg. The targets were partitioned into three types: on or within 30° of the current leg (4 targets), on or near another leg but within 30 degrees of the course heading of the current leg (3 targets), and on or near another leg but more than 75 degrees from the course heading of the current leg (6 targets). The first type (on the current leg) was viewed as a test of route knowledge. The other two types were viewed as tests of survey knowledge.

The second task was a test flight through the high-detail depiction of the navigational area. The heading indicator was removed from the flight display. The guidance was not shown and the participants were not given access to a map. Subjects were to navigate to the best of their ability from waypoint to waypoint solely by their memory of the navigational environment. Horizontal and vertical RMS errors from the desired course and from the prespecified altitude were recorded.

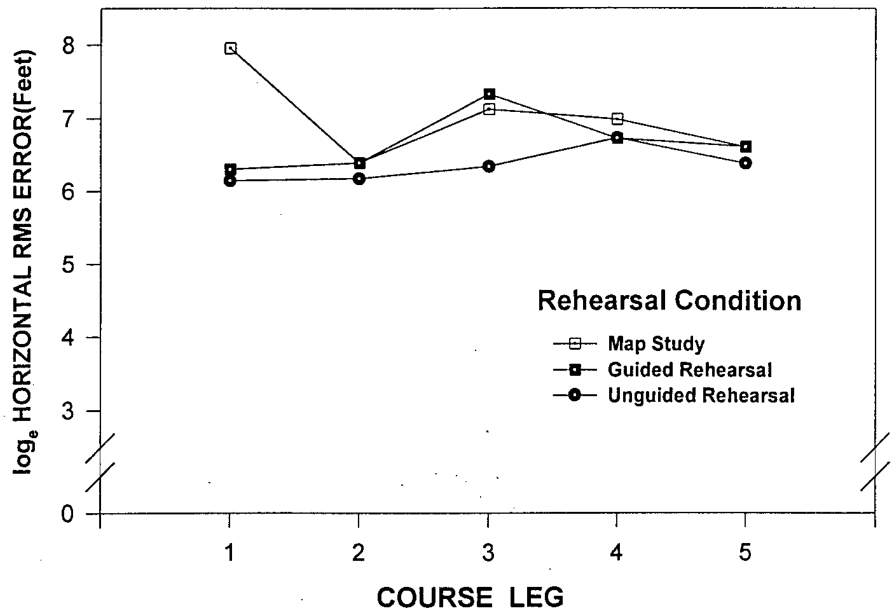
Results

Testing Session: Pointing Task

The performances of the map-study, guided-rehearsal and unguided-rehearsal groups were analyzed by MANOVA with Log_e time-to-target-acquisition and Log_e bearing error as performance measures. Univariate measures were considered valid for the Current Leg and >75°-bearing Other-Leg target sets (partial correlations = 0.20 and 0.02) but not for the <30°-bearing Other-Leg target set (partial correlation = 0.36). The only significant result was for bearing error with the >75°-bearing Other-Leg target set [$F_{(2,31)}=5.04$, $p=0.013$]. Paired contrasts showed a significant difference between the guided- and unguided-rehearsal groups [F (1,31)=9.77, p=0.004]. Bearing error was lower for the unguided-rehearsal group. Bearing error for the map-study group lay between bearing errors for the other two groups but was not significantly different to either.

Testing Session: Navigation Trial

The performances of the map-study, guided-rehearsal, and unguided-rehearsal groups were analyzed by MANOVA with Log_e RMS horizontal and vertical error as performance measures. Gender and cross-country time were entered as covariates. Multivariate tests were used because partial correlations between dependent measures exceeded 0.30 (range: 0.48-0.59). Wilkes Lambda was significant for legs 1 [Lambda (4,60)= 9.31, p<0.001], 3 [Lambda (4,60)= 3.25, p=0.018], and 4 [Lambda (4,60)=2.53, p=0.049]. For Leg 1, the paired contrast of the unguided-rehearsal group with the map-study group was significant [Lambda (2,31)= 11.19, p<0.001]. Leg 3 showed significant paired contrasts of the unguided-rehearsal group with the map-study group [Lambda (2,31)= 3.63, p=0.039] and with the guided-rehearsal group [Lambda (2,31)= 5.62, p=0.008]. For Leg 4, the paired contrast of the unguided-rehearsal group with the guided rehearsal group was significant [Lambda (2,31)= 4.86, p=0.]. The directions of the trends are shown in Figure 1.



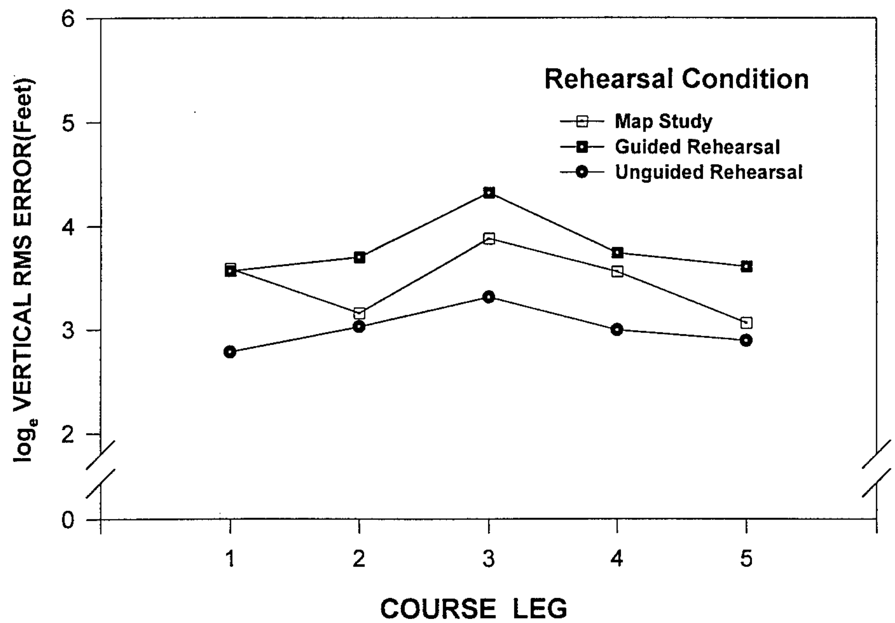


Figure 1. Mean lateral and vertical RMS errors (transformed to their natural logarithms) for the test flight of the map study, guided rehearsal, and unguided rehearsal groups.

Discussion

Mission Rehearsal for Development of Route Knowledge

Unguided mission rehearsal proved to be better preparation than map study for the test of route knowledge. There has been considerable discussion of the use of a simulator for mission rehearsal but these data are the first to offer objective support for this approach to preparing for a flight mission. In two of the five navigation legs of the test flight, unguided rehearsal demonstrated a clear and statistically significant advantage over map study.

Guidance for Development of Route Knowledge

The availability of guidance in rehearsal had a negative effect on navigational performance in the test phase when guidance was no longer available. Those effects were evident primarily on altitude control in this experiment. The guidance manipulation was directed at impacting navigational performance so any differences in vertical error between groups can be taken as an attentional or workload effect. Especially when course deviation errors are similar, differences in altitude error suggest that participants were working harder or diverting more attentional resources from vertical control to achieve a satisfactory level of horizontal control.

Participants who rehearsed with the guidance were able to maintain an accurate course on all but one leg in the test trial, but did so at some cost in cognitive workload as shown by their relatively large vertical error. Thus, while these participants could identify sufficient visual features for good navigation, that identification apparently demanded more effort. This higher level of demanded effort continued through all legs of the navigation task, suggesting that it is a particularly robust effect. In contrast, the unguided-rehearsal participants maintained a low level of vertical error, indicating that they had to divert relatively little attention to detection and recognition of navigational features.

Guided rehearsal might assist performance in a subsequent unguided test trial if navigational errors or workload during unguided rehearsal would be so great that they would disrupt familiarization with the course. In this experiment horizontal errors were larger during unguided rehearsal but only once did a participant in that group stray so far from course that the automatic reset procedure was activated. The similarity of vertical error scores during guided and unguided rehearsal suggests that there was no difference in workload between these two conditions. This lack of disruptive errors or of differential workload may have precluded the possibility of any enhancement in the test trial from guided rehearsal.

The negative potential of guidance is that it may divert attention from the navigational features that should be attended to if mission rehearsal is going to enhance performance on a navigational exercise. The enhanced rehearsal performance with guidance indicates that participants did attend to the guidance feature with a possible cost in attentiveness to navigational features. The lowered performance in the test flight suggests that this inferred diversion of attention from the navigational features had a deleterious effect. We continue to believe that guidance can assist in transfer to an unguided exercise but only if it focuses attention on critical information. For constant guidance as used here, workload or error must be so high for unguided rehearsal that they preclude meaningful learning, or else some form of adaptation or withdrawal as tested by Lintern (1980) will be necessary.

<u>Map Study for Development of Survey Knowledge</u>

Survey knowledge remains important even for a prespecified course because unanticipated events may require a diversion to a new course. The prevailing view in the literature is that survey knowledge is better developed by map study than by active rehearsal of a specific route (Thorndyke & Hayes-Roth, 1982; Williams Hutchinson & Wickens, 1996). Although not necessarily invalidating the results of those other studies, our results show no advantage for acquisition of survey knowledge from map study versus active rehearsal of a specific route. While guided rehearsal resulted in poor acquisition of survey knowledge as revealed by the >75-degree bearing Other-Leg target set of the pointing task, unguided participation of the rehearsal or of the map study form resulted in equally good acquisition of survey knowledge.

The conflicting ideas regarding the acquisition of survey knowledge indicate that a more comprehensive test of survey knowledge is needed. An active control test in which participants are required to divert to a new waypoint or to adjust the route while part way through a preplanned route would seem to offer a more valid test of this issue. It was not possible to undertake such a test of survey knowledge in the present experiment but it is an approach we plan to consider for future work.

Empirical exploration of information for landing.

An experiment was conducted to further explore how the skill of landing an aircraft may be guided via information obtained from the environment. Pilot control of an aircraft during simulated landings was investigated through manipulation of the information in a visual display. Prior research has shown that both the placement of the horizon and the inclusion of ground texture can affect pilot performance during aircraft landings. This experiment investigated the effects of these factors upon pilot descent path control. The dependent measure used was angle to aimpoint.

Method

Subjects. The subjects for this experiment consisted of 12 male pilots between 19 and 30 years of age. Each subject was paid for his participation. All subjects had normal or corrected vision. The subjects had an average of 230 hours of flight time, ranging from 150 hours to over 300 hours.

Apparatus and Displays. The experiment was conducted in an ILLIMAC flight simulator. The ILLIMAC is a fixed-base, digital light aircraft trainer. Wing flaps were preset to a specified level and the attitude, altitude, vertical speed and heading indicators were all deactivated for this experiment. Information from airspeed and engine power remained available to pilots. A Silicon Graphics IRIS Elan computer provided an interactive, computer-animated, real-time landing display of moderate scene detail. This display, under default conditions, presented a horizon, full ground texture, buildings and a runway (Figure 2). In perspective gradient conditions the ground texture and buildings were replaced with fifteen lines on each side of and parallel to the runway, converging at the horizon. The visual display was refreshed 12 times a second.

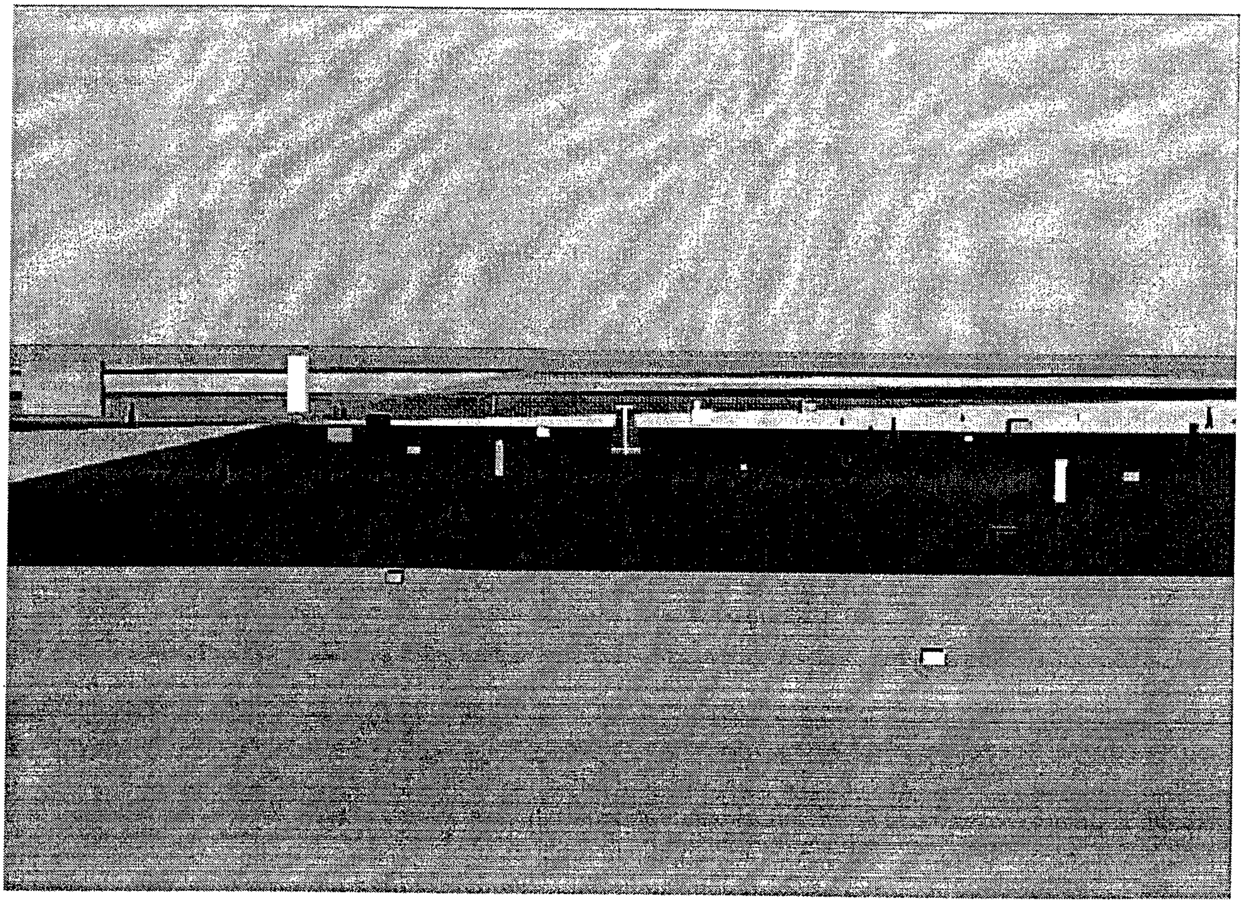


Figure 2. A black and white representation of the colored visual display with full ground texture.

Three features were incorporated into the experiment. First, to reduce non-visual strategies, headwinds were used ranging from 0 to 25 miles per hour. These headwinds, which varied between trials but remained at a fixed value within trials, ensured that pilots did not fly the approach by settling on a fixed set of aircraft parameters and calibration of a set of tactual and proprioceptive information for control. Second, a "short trial" where the pilot was stopped a short distance from the runway was used to reduce identification of horizon bias. Third, augmented feedback was included during the first calibration trial of every block. Red F-poles were switched on to show the correct flightpath when the pilot was off the glideslope (and switched off when the pilot was on the glideslope) to help recalibrate subjects to the correct glideslope.

Design. The independent variables of interest were location of texture and horizon bias. Location of texture was varied at four levels: foreground (half of the visual scene before the runway), background (half of the visual scene behind the runway), full (texture along the entire visual scene) and none (texture removed from the visual scene). The no-texture condition served as a control condition. The horizon was presented at three levels of bias: high, low and normal. The dependent measure was angle to aimpoint.

Procedure. Subjects were tested over five sessions in the ILLIMAC simulator. The first session was a practice session of thirty trials which gave pilots a chance to become familiar with the simulator and the methods being used. Subjects were presented with a blank screen at the start of each trial. No visual information was displayed until the subject pressed a button to initiate the trial.

The four experimental sessions required two hours each. There were 60 trials in each session. Each data session was performed from one to three days after the previous session.

Experimental sessions were formatted into ten-trial blocks. Each block of trials consisted of two calibration trials and eight experimental trials. The two calibration trials consisted of one trial with augmented feedback followed by one trial with full display conditions as seen in Figure 2. Each calibration trial was flown through touchdown and experimental variables were not manipulated. Headwinds were included other trials. They were consistent within a trial but varied between trials such that each subject experienced the four levels of headwinds twice in a block of trials. The experimental condition viewed remained constant within a block but altered between blocks.

Data Analysis. The means of the dependent measure of angle to aimpoint are reported here as well as the means of the between-trial variability. While between-trial variability is not typically reported, it is used here to provide information about the pattern of trial-to-trial stability in descents. This knowledge is important because it provides a measure of how well the information available to pilots supports behavior. This measure of stability is lost when only the normal between-subject variability is reported.

Results

Figure 3 provides a graphical representation of the means. The main effect of horizon bias was significant [$F(2, 22) = 11.94$, $p < .01$]. This indicates that the horizon manipulation affected pilots as predicted by the H-angle hypothesis. The trend suggests that pilots flew lower approaches when presented with a high horizon than with a normal horizon. The trend also shows that pilots flew higher approaches when presented with a low horizon than a normal horizon. The interaction of ground texture with horizon bias was not significant [$F(6,66) = .45$, $p=.84$]. Nor was the main effect of ground texture location [$F(3,33) = 1.01$, $p=.40$]. These results suggest that pilot descent path guidance was not affected by changes in ground texture location.

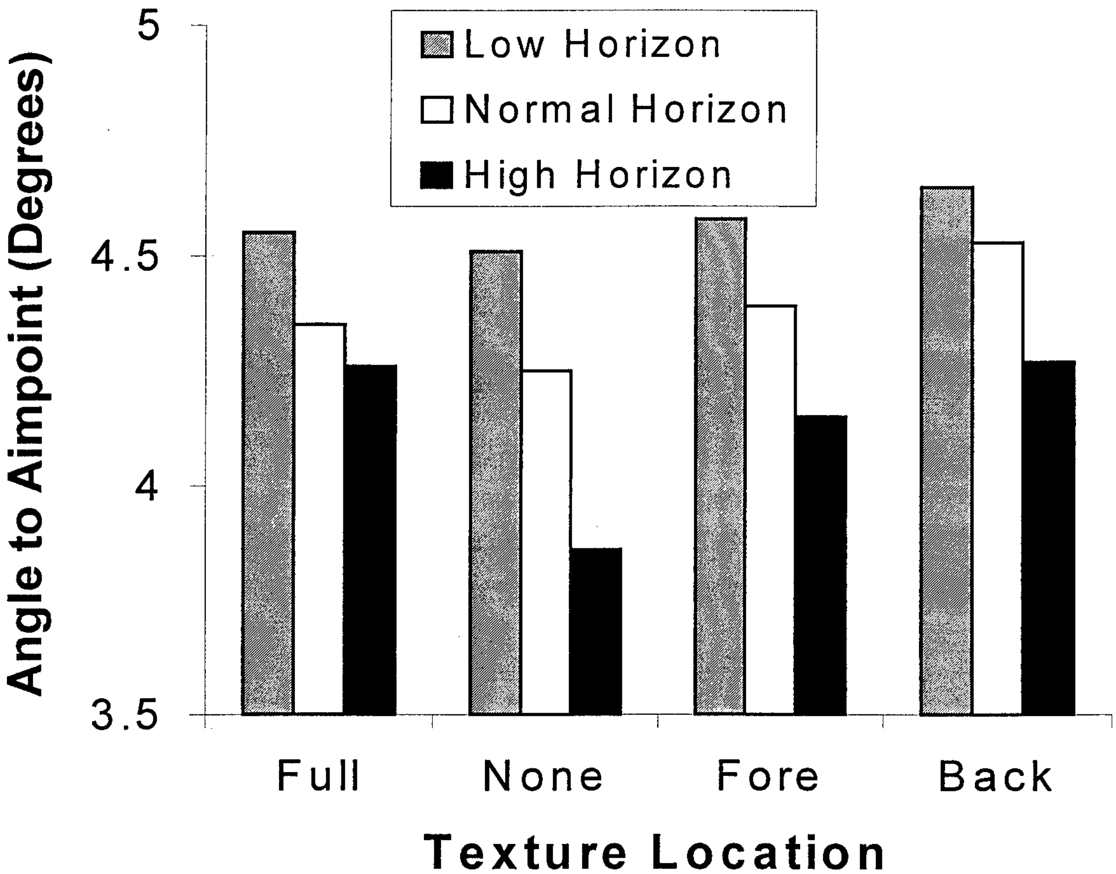


Figure 3. Texture and horizon versus angle to aimpoint.

Figure 4 provides a graphical representation of the between-trial standard deviations. Between-trial variability showed a significant main effect of texture location [$F(3, 33) = 10.61$, $p<.01$]. The effect is due to variability in the no-texture condition being considerably higher than in any of the other three conditions. A borderline significant interaction [$F(6,66) = 2.23$, $p=.05$] was also present. This interaction appears to emerge from the fact that the pattern of horizon biases reverses both between the full and no texture conditions and between the foreground and background conditions. The main effect of horizon bias was non-significant [F(2,22) = .60, p=.56]. This would suggest that horizon bias did not have an effect on between-trial variability.

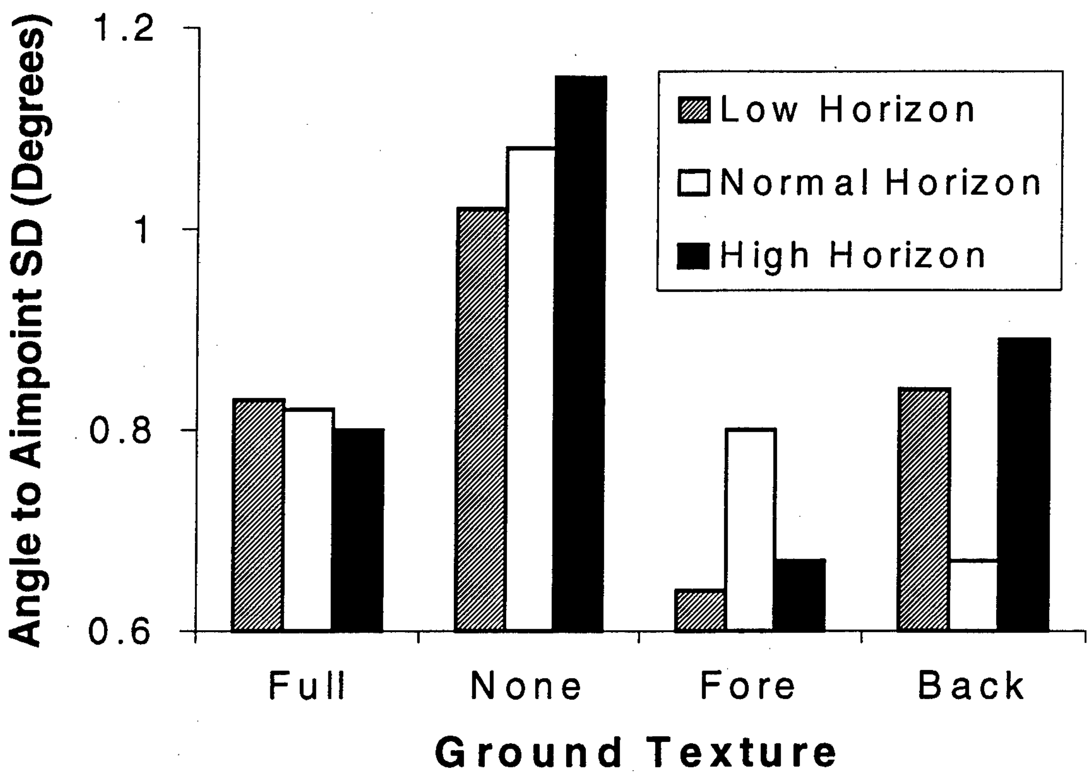


Figure 4. Texture and horizon versus angle to aimpoint between trial

Discussion

Figure 3 shows that pilots were affected by the horizon bias manipulation. As predicted, pilots in a low horizon condition made high approaches compared to the unbiased condition while pilots in the high horizon condition made low approaches compared to the unbiased condition. This result is consistent with previous studies and suggests that pilots are sensitive to the invariant H-angle property and use it to guide their aircraft descent. These results add to previous studies in that the biases can be compared to a baseline horizon and support the full extent of the H-angle hypothesis. Prior to this study, knowledge about the effects of the H-angle alone was limited to the fact the high horizon induced lower approaches than the low horizon. However, it was unclear to what extent the biases in performance were different from normal performance. The introduction of a normal horizon verifies that the low and high horizon manipulations do indeed bias pilot performance in the hypothesized directions.

The lack of effect via ground texture in the means indicates that ground texture does not directly affect pilot descent control. This is contrary to some experimental evidence (e.g. Lintern & Walker, 1991; Lintern & Koonce, 1991) that revealed that landings under conditions of no texture were lower than approaches made with texture. While ground texture does not directly affect descent control, the between-trial variability (Figure 4) shows that the inclusion of ground texture reduced variability. This result suggests that pilots use certain information within the ground texture to maintain their consistency. This information must be something other than the H-angle, since no main effect of horizon bias was present in the variability plots. These results suggest that information from ground texture does affect glideslope stability.

Together these results give a clearer picture of the effects of ground texture and horizon bias on pilot performance. It is clear that pilots use the information from the H-angle to guide aircraft landings and the inclusion of ground texture stabilizes the approach. This work is reported more fully in Doherty and Lintern (1999).

Analytical exploration of information for landing

Judgment of slant angle from texture gradients may be the primary strategy used by pilots to maintain a constant angle of descent towards a runway aimpoint for landing without visual aids. A normally textured terrain generates a number of gradients. One or more of these might be involved in the judgment of slant. A texture gradient refers to the regular decrease in visual angle of same-sized features as they recede from the point of observation. In natural terrain, features are not of the same size but there is a globally stochastic regularity of size that permits extraction of gradients (Stevens, 1981). The three gradients considered in this paper are those of perspective, compression, and size. The perspective gradient is based on the lateral projection of features, the compression gradient on the longitudinal projection of features, and the size gradient on the solid angle of features.

A gradient is a rate of change, which in mathematical terms, is a differential. Visual gradients must be specified in terms of angles subtended at the eye. For example, the perspective gradient can be specified as the change in b, the horizontal angle subtended at the eye by equally sized features, as the line of gaze is swept along the surface of the ground plane in a line directly away from the observer (Figure 5). The differential involving b might be constructed around a function in x (i.e., $b = f(x)$) where x is the ground distance in texture units from the observer (to give db/dx) or around a function in r (i.e., $b = f(r)$) where r is the slant angle or the angle of line of gaze to the ground plane (to give db/dr). For purposes of later analysis I will refer to the differential with respect to the slant angle, r.

b = f(r), gradient = db/dr
relative gradient = f'( )/b

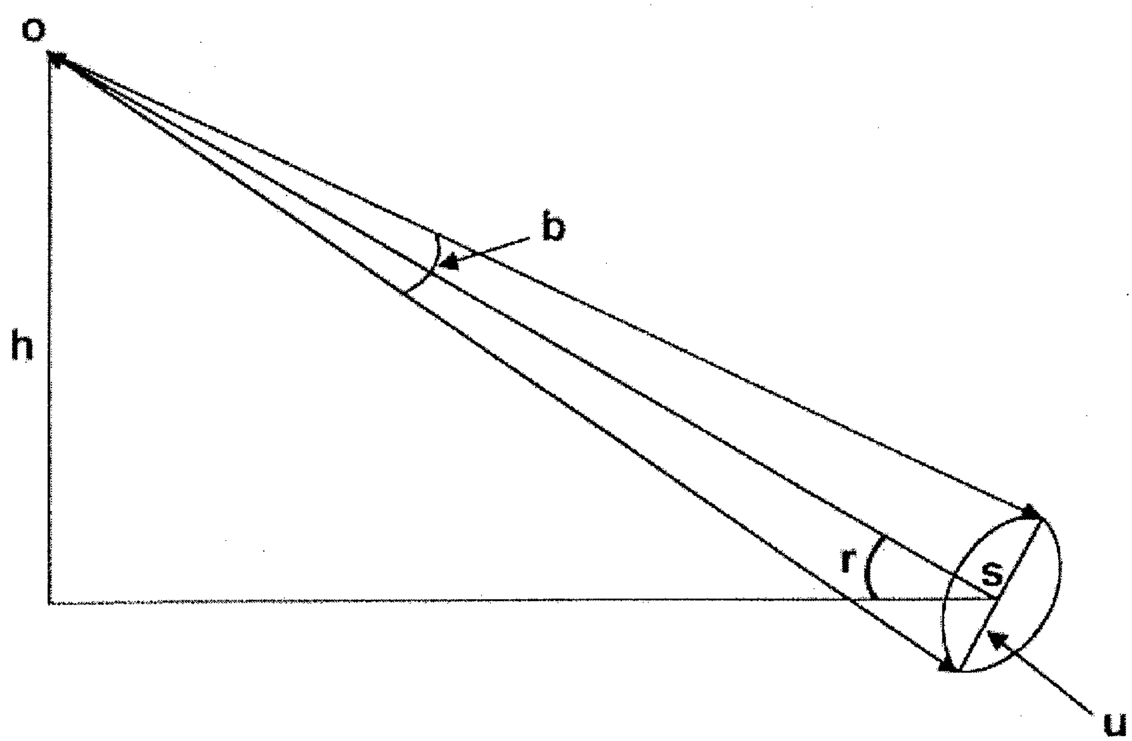


Figure 5. The angle b is the lateral angle subtended at the point of observation o by a texture element of lateral size u. A perspective gradient is based on the change in this angle as the line of gaze os is swept along the ground plane in front of the observer. The absolute perspective gradient is the rate of change of angular size of texture elements (db/dr) and the relative perspective gradient is (db/dr)/b. The height of the eyepoint is denoted as h.

The specific focus of this work was to assess whether the gradients that can be extracted from a texture conform to the requirements of perceptual invariants. The most fundamental issue is whether a gradient maintains a constant value during a constant angle descent and whether it changes noticeably for changes in that angle. To be noticeable the change in value must be above threshold for functionally relevant changes in angle of slant. In addition, it would be useful if the behavior of the invariant was not influenced by changes in the size of the texture elements that instantiate the gradient.

To assess whether a change in gradient value is of functional significance it is necessary to provide a standard. In this analysis the standard is based on variations in gradient values that accompany functionally significant changes in descent angle with other factors held constant. The Precision Approach Path Indicator shows a noticeably high or low condition at ±0.2 degrees. The criterion for this analysis is to accept that texture gradients are functionally adequate for descent path control if their departures from invariance from 12,000 feet from runway aimpoint to 375 feet from runway aimpoint do not exceed the variations in gradient values that would correspond to glideslope errors of ±0.2 degrees. Three hundred and seventy five feet at an angle of 4° corresponds to an altitude of 25 feet which is approximately where pilots initiate their roundout.

In mathematical terms, the requirement is to examine the invariance of d(f(r))/dr where r represents the angle between the line of sight to the runway aimpoint and a line on the ground surface from directly beneath the point of observation to the aimpoint. This is the gradient that is implicated in the proposition that pilots judge their glideslope from the perspective convergence of a runway's sides. While Hasbrook (1975) and Wulfeck and Queen (1975) appear to regard this form of a perspective gradient as important, Purdy (1958) proposed that the relative gradient is the potential source of information. Relative gradients are scaled against feature size and can be defined as (d(f(r))/dr)/f(r). The invariance of relative gradients was also examined. To distinguish the two forms they are referred to as absolute and relative gradients respectively.

Method

Mathematica version 2.2.3 was used for symbolic transformations, calculations, and plots.

The Value of a Perspective Gradient

To find the value of a perspective gradient it is necessary to substitute the value of b in terms of the variable r to permit differentiation with respect to r.

From:

$\tan(0.5\ b) = (0.5\ u)/os$, and

$\sin(r) = h/os$,

$b = 2\arctan[(u \sin[r])/(2h)]$

$(db/dr)/b = [\ u \cos(r)]/[\{2\ h \arctan[u \sin(r)]/[2\ h]\}\ \{1+[u^2\ \sin(r)^2]/[4\ h^2]\}]$

Strategy of Analysis

In that descent angle, r, is the parameter in the equation that represents the controlled variable, the differentiation is always with respect to r. Attention is paid here to descent angles typically used in landing a light aircraft. Here I show the values of absolute and relative gradients for selected descent angles between 825 to 25 feet altitude. This corresponds to an approximate ground distance from aimpoint of 12,000 to 375 feet, assuming a 4-degree descent path.

Results

Figures 6a and 6b show the values of db/dr and (db/dr)/b from 825 to 25 feet altitude on the approach to landing. The values are plotted for slant angles of 3.8, 4.0, and 4.2 degrees. The lateral size of texture elements is 1 foot. The three plots in Figure 6a are not identical but the differences are too small to detect in the plots. Figure 6a shows that db/dr is not invariant over a constant angle of approach, that it varies with size of texture element, and that the differences for variations in descent angle are minimal in relation to the differences generated throughout a constant angle of approach. In this regard, db/dr fails as a perceptual invariant on all three criteria that must be satisfied. For Figure 6b the deviations from invariance for each of the three plots are too small to detect in the figure and are minimal in relation to the differences due to variations of 0.20 degrees in descent angle. In that deviations from invariance, at least up to the roundout, are much smaller than differences generated by minimally functional changes in glideslope angle, (db/dr)/b conforms to the requirements for a perceptual invariant.

Discussion

These analyses reveal that the perspective gradient could support guidance along the landing descent path. Although a texture gradient in itself could not be useful, a gradient proportionalized against size of texture elements could support descent-path control. While not mathematically invariant, the departures from invariance of these proportionalized or relative gradients are too small to be functionally significant. In addition, relative gradients are sensitive to minimum functionally significant changes in angle of descent whereas absolute gradients are not. Thus, relative gradients satisfy the formal requirements of an invariant for control of action. A report of this work has been accepted for publication (Lintern, in press).

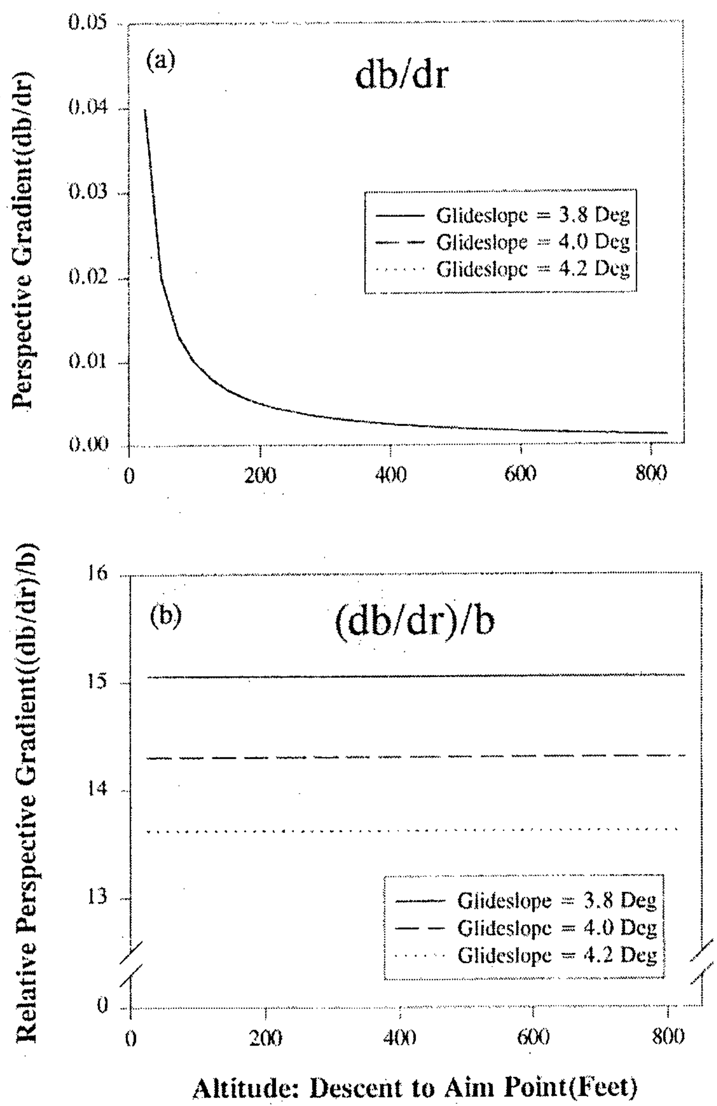


Figure 6. Values of absolute and relative perspective gradients over an altitude range of 825 to 25 feet for glideslope angles of 3.8, 4.0, and 4.2 degrees and texture elements of lateral dimension of 1.0 foot. These gradient values are dimensionless.

Summary

The central claim put forth in this proposal is that transfer can occur only when critical similarities are maintained across the training and transfer tasks. I have argued that informational invariants constitute properties that define critical similarities and that they are essential components of all tasks that can be learned. If critical invariants (specifically, those that pose a meaningful learning challenge) remain unchanged, transfer will be high even when many other features of the environment, context, or task are changed.

The development of a coherent account of skill transfer has proved to be a struggle throughout the past century of psychological and educational research. Commencing with the notion of formal discipline (Woodrow, 1927), a variety of views have emerged, none of which has been able to provide an account that offers a clear research agenda or comprehensive training principles. In the contemporary cognitive style, it is common to postulate a hypothetical construct such as psychological fidelity (Goldstein, 1986), instance memory (Logan, 1988), production rules (Singley & Anderson, 1989), or schemata (Schmidt, 1975). Such constructs are, however, inferred from behavioral data of the type that they are intended to explain. Circularity is a significant problem. In contrast, informational invariants are real and their existence can be verified independently of the transfer effects they are thought to impact. Thus, the informational perspective has the potential to place design of instructional systems on a sound theoretical basis.

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